Finalizing the DTAG: Implementation and Testing of Design Improvements for Reliability and Availability

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LONG-TERM GOALS

Here we propose to make design changes to improve reliability and manufacturability of the Dtag, a sound recording multi-sensor tag. Additionally, we will set up a lease pool that will be used to provide the community with access to tags at a moderate cost per project while also allowing for monitoring of tag field performance.

OBJECTIVES

Dtags have proven to be a valuable tool for the study of marine mammal acoustics and fine scale motion. The success of the Dtag has resulted in an increased demand for the instrument from researchers both within the Navy and the marine mammal community. However, the current Dtag design has cost, robustness, and reliability issues that make it unsuitable for the scaled-up manufacturing necessary to meet demand. To address this, we will improve reliability and manufacturability of the tag, and evaluate the new design by fabricating a small number of proto-type tags for testing. Additionally, this project will implement these design changes to create a pool of field-ready and cost-effective Dtags available to marine mammal researchers.

APPROACH

The objective of the origional Dtag-3 design was to expand the capabilities of the Dtag-2 (longer duration, wider bandwidth, support for more sensors) while decreasing the size of the instrument to make it suitable for smaller delphinids. The new design was also needed because Dtag-2 components

had become obsolete. To meet the challenge of reducing size while increasing capabilities, we explored several different packaging methods. Unfortunately, some of these new compact fabrication methods have decreased the robustness of the system leading to tag failures in the field. This project involves four tasks to be performed over the course of two years. They are: **1)** implementation of design changes to address tag failure modes; **2)** improved design for manufacture; **3)** a small test build (4 units) of the new Dtags, which will be tested rigorously; and **4)** the fabrication of a quantity of the revised tags for use by the marine mammal science community via a lease pool. The development of this pool will alleviate the current Dtag availability bottleneck while providing a mechanism to incorporate experience from the field about long-term reliability of the tags.

WORK COMPLETED

I. Design Changes to Address Tag Reliability

Objective: To create a new Dtag with improved performance, reliability and longevity in the field we have created a design that addresses the following key five limitations present in the current Dtag: pressure tolerance of the electronics, corrosion failures related to sea water ingress, floatation, light sensitivity, and hydrophone vulnerability.

Methods and Results:
1. Problem: Sea water ingress. Potential leakage points in the external urethane shell have been identified in the current Dtag-3 design. These primarily arise from components which necessarily penetrate the barrier such as the salt-water switch, the release wiring and the USB connector. Flexure of the shell when the tag is attached to a swimming animal gradually weakens the bond at these joints opening ingress paths for water. Once water has penetrated this barrier, inconsistent bonding of the urethane shell to interior wires and metal shield layers leads to water movement into the electronics cavity, battery and external USB connector causing failure of one or more of these subsystems.

2. Problem: Pressure tolerance of the electronics. Previous versions of the Dtag used an oil or gel-filled bladder to create a pressure tolerant environment for the tag electronics. The oil/gel floods the space around the electronic components and is essentially incompressible so that, even though, the components experience ambient pressure, there are no shear stresses due to pressure differences. A drawback of an oil-filled housing is that, if water is able to enter the housing, it will contact the circuit causing corrosion and eventual failure. This was a significant cause of failure in the Dtag-2. The initial Dtag-3 design also used oil but due to manufacturing difficulties related to the smaller dimensions of the new tag, this was later changed to a two-part polyurethane gel. However the mixed resin was found to be too viscous to flow completely under the miniature tag components, resulting in electronic component failure at pressure.

3. Problem: Floatation. Due to the replacement of oil with an encapsulant with higher specific gravity, the current Dtag-3 floatation no longer floats the tag reliably in fresh or brackish water. Although the tag is usually used at sea, the lack of floatation could be an issue if the tag released from an animal in a region with a low salinity surface layer e.g., from a river outflow. Low buoyancy also affects the stability of the tag when it is floating at the surface leading to intermittent reception of the VHF beacon in the tag in high seas.

4. Problem: Light sensitivity. Some of the miniature electronic components used in the tag are susceptible to light. In particular, fluctuating light levels cause large step changes in the pressure and magnetic field signals which are difficult to remove in post-processing. As the casting materials used

for the external shell are translucent, the tag data can be strongly affected by light when the animals are near or at the surface.

5. Problem: Hydrophone vulnerability. Front mounted spherical hydrophones have failed following field deployments. These failures are likely the result of a direct impact to the exposed sensor while the tags are being handled. Hydrophone failures were not an issue with the Dtag-2 design because the sensors were more centrally located and the external polyethylene shell that formed the tag housing provided an additional layer of protection. However, the polyethylene reduced sensor performance, because air trapped between the shell and the sensor blocks sound when the animal is close to the surface. The polyethylene shell was eliminated in the Dtag-3 design to improve acoustic performance, but the hydrophones are more vulnerable as a result.

II. Design for Manufacturability

Objective: A key to reducing the overall cost of the tag and improving tag reliability is enhanced design for manufacturability.

Methods and Results: We have divided the current single unit approach into 3 main sub-assemblies (Figure 5): 1) foam sub-assembly, 2) sensor sub-assembly, and 3) Electronics sub-assembly. This separation enables rapid quality assurance on individual sub-assemblies, leading to improved yield, increased throughput, and reduced cost. The foam sub-assembly is made up of the tag floatation, the VHF antenna assembly, and the saltwater switch. The sensor sub-assembly contains the two hydrophones, the external pressure sensor, and an interconnect board. The electronics sub-assembly consists of the main electronics, a protective mechanical structure, the release, and the external USB connector for data offload and recharge.

The use of interconnect boards and pin headers to replace the intricate wiring of the single unit DTAG is key to this modular design. The improved connections between the subassemblies eliminate leakage pathways that had resulted in tag failure while also reducing tag assembly times. These connections required the design of custom boards for the sensor interface, VHF interface, and USB interface, Figure 6. The three sub-assemblies have been designed to operate as individual units for stand-alone testing. The identification of performance problems with individual units before final assembly will enhance the overall manufacturing yield.

III. Life Cycle Pressure Testing of the Tag Electronics

Objective: A small set of tags has been assembled for testing and evaluation in the lab (n=4). Pressure testing facilities were used to simulate field deployments in a condensed period of time under controlled environmental conditions. To evaluate the performance of this assembly we fabricated four prototype assemblies consisting of the electronics and sensor subassemblies, Figure 9. In this accelerated life time testing we are looking to simulate conditons the tags will experience during a field deployment and look for pressure induced stress and strain failures to the printed circuit boards. The advantages of testing without the urethane overpotting are that we test the core system in the worst case scenario while also being able to track down any failure modes that occur. Additionally, the pressure chamber was used to calibrate and evaluate performance of the externally mounted pressure transducer.

Methods and Results: Two different types of epoxy encapsulate were used with the tag prototypes. EpoTek 301-1 was used with Tag A and EpoTek 301-2 was used with Tags B-D. We began by using EpoTek 301-1 because of our experience with this product for electronics encapsulation in the past.

EpoTek 301-2 was selected at the vendor's suggestion after we experienced a partial component failure during initial tests. This product has a lower durometer and is more appropriate for the volume of material we are using to encapsulate the boards. Potting large volumes of EpoTek 301-1 can result in an exothermic reaction that can damage the electronics. Vacuum investment was used to encapsulate the cards in all four tags. The pressure transducer (Keller PAL3) was encapsulated in in flexible urethane at the front of the housing. Current Dtag circuit boards (Main V1.1 and Audio V1.1) were used for the test, but the newly designed interconnect boards were used for all of the tags. Prior to pressure testing all of the tags were 'bench' tested to ensure that they were operating properly. Pressure testing was conducted in two WHOI pressure testing facilities. The Smith facility was used for short term checks, tests of less than an hour, or for tests when the DUT (device under test) did not need to be closely monitored. The Blake facility was used for day scale testing (8-10 hours) when the DUT was monitored constantly. The tags recorded sensor data throughout the tests and three experimental protocols were used to evaluate tag performance.

RESULTS

I. Design Changes to Address Tag Reliability

1. Problem: Sea water ingress. Internal mechanical elements have been redesigned to simplify assembly and reduce exposed wiring and electronics, Figure 1. The USB connector and VHF circuitry are now located on the electronics sub-assembly and directly connected to the main tag electronics through pin headers and interface boards. These changes eliminate the extended wiring that made assembly difficult and created leakage pathways. Multiple water barriers are now used to enhance the encapsulation of the electronics, Figures 1 and 2. The electronics are first sealed in a low viscosity casting resins (epoxy) and the sensor assembly and battery are encased in a layer of urethane. Next, the entire assembly is cast in a second layer of urethane that also serves as the overall tag housing.

2. Problem: Pressure tolerance of the electronics. A low viscosity epoxy casting resin together with vacuum investment is used to ensure that electronic components are fully encapsulated, Figure 1. The fully cast electronic system will be impervious to water and pressure tolerant. One important consideration in moving to epoxy encapsulated Dtag electronics was placement of the pressure transducer used to measure the location of the tag in the water column. Moving from an oil-filled to epoxy encapsulated electronics cavity required relocating the pressure transducer. To accommodate the rigid low-viscosity casting materials and relocation of the pressure transducer, we have created a separate external sensing module consisting of the hydrophones and pressure sensor, Figure 1. The sensor module is encapsulated in urethane and connected to the electronics through a header and interface board at the front of the tag. Lab based pressure testing was used to test the new design and to calibrate the pressure sensor (see test results in section III). Additionally, Dtag-3 tags manufactured at St. Andrews that incorporate these encapsulation methods have been used successfully during opportunistic field testing conducted by Dr. Fleur Visser with both Risso's dolphins and deep diving Cuvier's beaked whales **(**See Section IV**).**

3. Problem: Floatation. The volume of floatation has been increased through the re-design of both the syntactic foam and the external shell. This re-design will be closely integrated with the other modifications listed here to ensure that the final device has adequate floatation.

4. Problem: Light sensitivity. Susceptible parts will be replaced with components that are not light sensitive. However, to avoid any other problems of this kind, we will manufacture the external tag structure from a material that blocks out light, Figure 4.

5. Problem: Hydrophone vulnerability. External housing material around the hydrophones has been increased, Figure 2.

II. Design for Manufacturability

The components have been designed and selected with scaled up manufacturing in mind. Individual components that make up the sensor module, for example, are assembled by outside vendors. The interface board comes populated from the board house and the hydrophone spheres come wired and assembled. Further we have been working with external vendors (1900 Engineering, LLC), on large volume encapsulation of the sensor sub-assembly. Figure 7 shows the components that make up multiple sensor modules positioned in a mold before encapsulation. The mold shown in the figure was designed under the advisement of engineers at 1900 Engineering. Importantly, the mold design makes a scaled up design straight forward. Additionally, we are also working closely with 1900 Engineering on the design for assembly of the foam and the molds for the final encapsulation of the tag assembly.

III. Life Cycle Pressure Testing of the Tag Electronics

Epoxy Test 1: Only Tag A, with EpoTek 301-1 epoxy, was evaluated with this protocol
Pressure protocol and results: An initial single cycle test where the tag was taken to 3000 psi and held for 30 min was performed and passed by the tag in the Smith tank. Next, a 24 hour test with repetitive pressure loading was conducted where the tag was quickly cycled to 1000, 2000, 3000 psi 40-50 times. After examining the tag data following this test it was determined that an individual component had partially failed. This failure affected how some of the sensor data was recorded, but did not affect the audio data. The tag is still usable but this component failure led us to the change to Epo-Tek 301-2 for the remaining prototype tags.

Epoxy Test 2: Tags C and D, with Epo-Tek 301-2 epoxy, were both evaluated with this protocol
Pressure protocol and results: A more realistic "Dive Cycle" Testing protocol was used to test the two tags simultaneously at Blake facility. The dive cycles varied between 'shallow' (1000 psi) to 'deep' (2000 psi and 3000 psi), Figures 10 and 11. To simulate the dives, the pressure was slowly increased to the maximum depth, held for 10 min, slowly decreased to 0 psi, and then held for 5 min. These cycles were then repeated as many times as possible during the next 8 hours. Over four days of testing, the tags were cycled to depth a total of 97 times, including 9 cycles to 2000 psi and 5 cycles to 3000 psi. The tags were held at pressures of at least 1000 psi for 22.5 hours during the testing. Both tags successfully passed the protocol with no electronic component failures.

Epoxy Test 3: Tags C and D, with Epo-Tek 301-2 epoxy, were both evaluated with this protocol
Pressure protocol and results: To increase the number of cycles and the time spent at the highest test pressures two additional days of cycle testing were conducted. The tags were cycled from 0 psi to 3000 psi and held for about 30 minutes at pressure, Figure 11. These tests resulted in an additional 16 cycles to 3000 psi and 13.5 more hours at pressure.

Pressure Sensor Testing: The transducer was calibrated in the pressure chamber against a reference transducer (Measurement Specialties MSP-600). Once calibrated the transducer was then moved to duration and cycle testing. The goal of this testing was to determine whether the transducers would hold a calibration over a period of pressure cycles. After over 600 hours of testing the PA3L sensor held its calibration. Figure 12 presents data from the PA3L sensor, and includes a calibration check for the transducer at the 344 hour mark of testing (Top plot).

Summary: During the course of the simulated life cycle testing two tags were pressure cycled over 100 times and were held at pressures of at least 1000 psi or greater for more than 36 hours without failure. Specifically, the tags were cycled to at least 1000 psi 113 times, to 2000 psi 20 times, and to 3000 psi 20 times. No failures or other issue were observed in either tag. These results indicate that vacuum investment casting with Epo-Tek 301-2 epoxy is appropriate for the fabrication of future tags.

IV. Opportunistic Field Testing:
Field trials have been conducted with tags built using the design concepts presented in Section I. The field work was conducted by Dr. Fleur Visser in the Azores during the summer of 2015. During the work, several Risso's dolphins and three Cuvier's beaked whales were tagged, and multiple deep dives to greater than 1500 m were recorded from the tagged beaked whales. The tags successfully collected data during all trials. The researchers reported occasional connectivity issues with the USB connector and one VHF antenna was broken during the course of the field work. These issues with early prototypes have been addressed in the final tag design. We have also set up a database containing details of problems identified in the field. This direct information from users in the field will be used to continually improve the design of the DTAG and monitor resulting performance.

V. Synergistic Activities:
Along with the design, testing, and fabrication of the robust and manufacturable DTAG we are currently working with Dr. Patrick Miller to the design a separate tag system that will be compatible with the Aerial Rocket Tag System (ARTS). For this work, the electronics and sensor sub-assemblies will be packaged as a standalone unit. Dr. Miller and his team will design an alternative housing system for the tag. The housing system will include the floatation, VHF transmitter, suction cups, and the interface with the ARTS system.

VI. Fabrication and implementation of the Tag Pool:
Based on the successful results from the experimental pressure testing and feedback from opportunistic field work, we are currently finalizing the design that will be used to fabricate tags for the lease pool. The initial stock of tags will be fabricated and tested during the fall 2015. The pool tags will be avalible for month-to-moth lease beginning in early 2016. The goal of the lease program is to become self-sustaining. To this end demand for tags and feedback from from the community will be used to refine the business model to achieve the duel goal of providing affortable tags to the community while achieving sustainability.

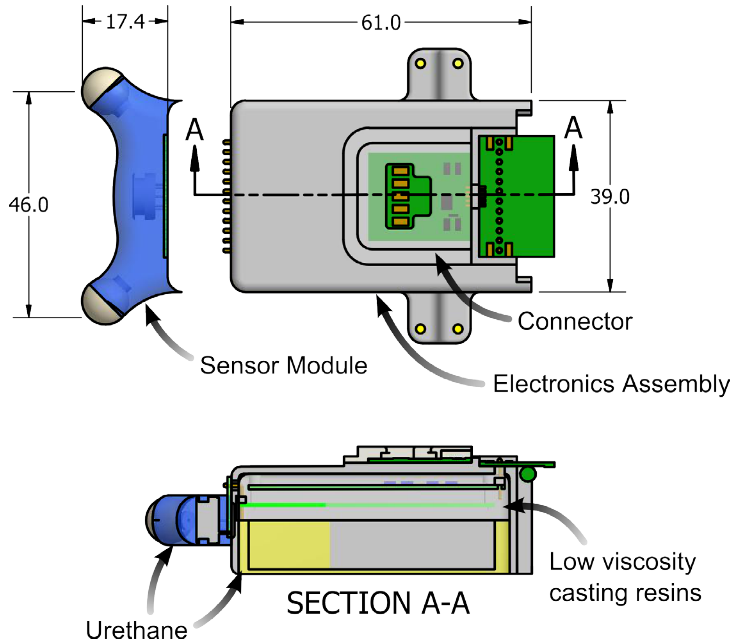

Figure 1 A drawing of the electronics and sensor sub-assemblies that illustrates the low viscosity epoxy and urethane used to provide pressure compensation and waterproofing. Dimensions in (mm).

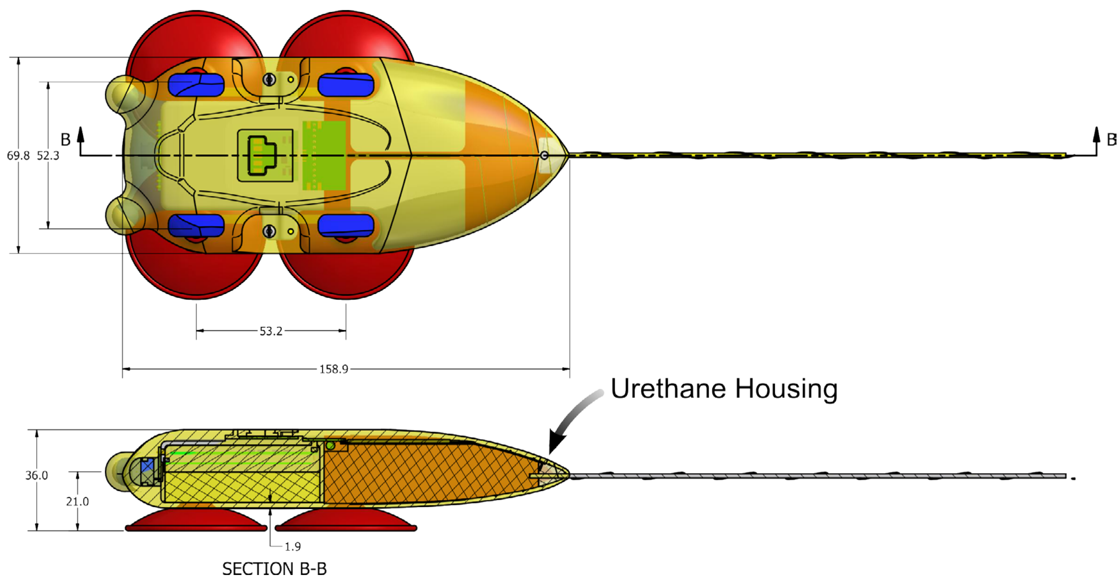

Figure 2 A drawing of the encapsulated tag assembly with suction cups. The external urethane housing acts as a second water barrier in addition to the low viscosity epoxy and urethane used with the sub-assemblies. In addition to acting as a water barrier, the external housing protects the hydrophones, provides the attachment point for the cups and acts as a hydrodynamic fairing. The transparent coloring of the housing is for illustrative purposes only. All dimensions in (mm).

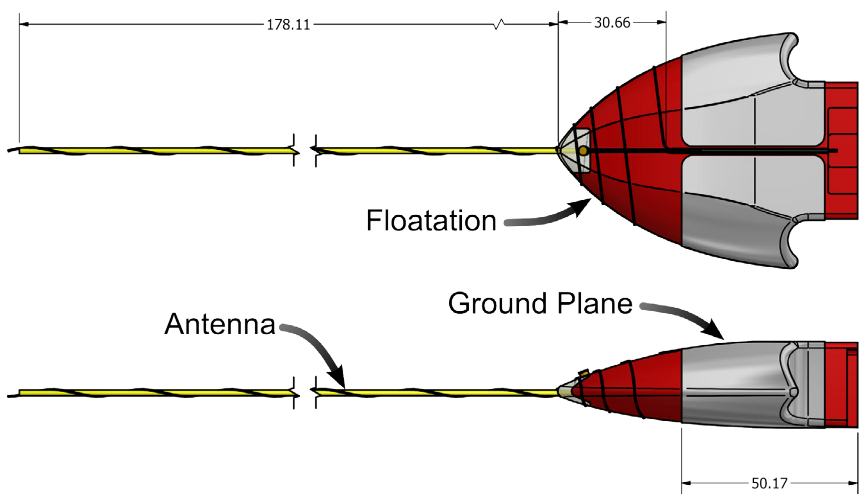

Figure 3 A drawing of the foam sub-assembly shown with the VHF antenna wire and ground plane. Syntactic foam is be used for the floatation. All dimensions in (mm).

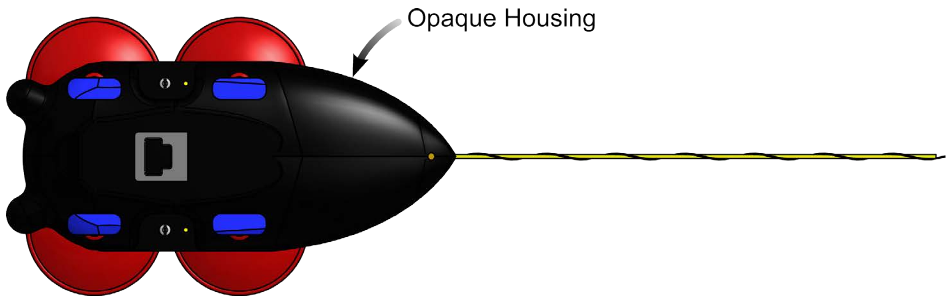

Figure 4 A drawing that illustrates the use of an opaque material for the tag housing to address the light sensitivity issue.

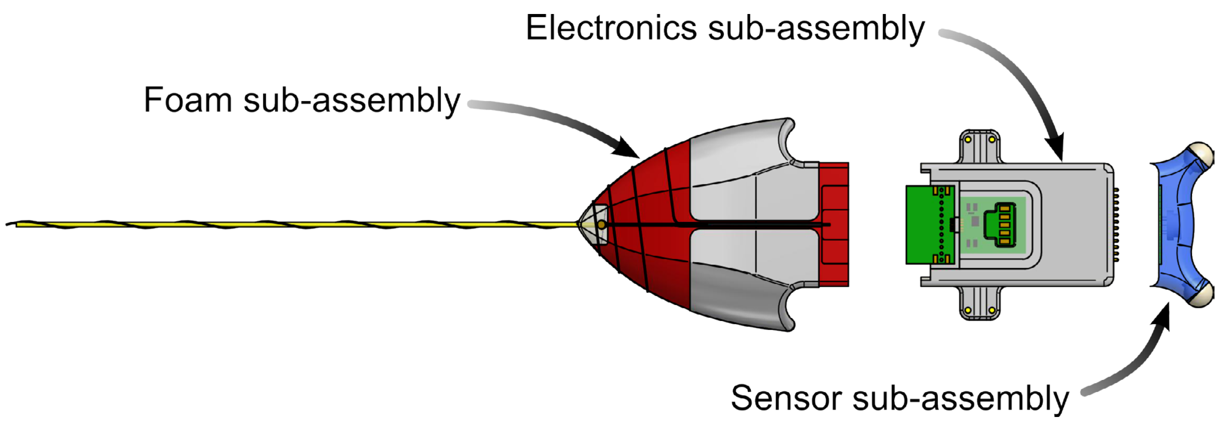

Figure 5 Illustration of the three main subassemblies that make up the new Dtag design.

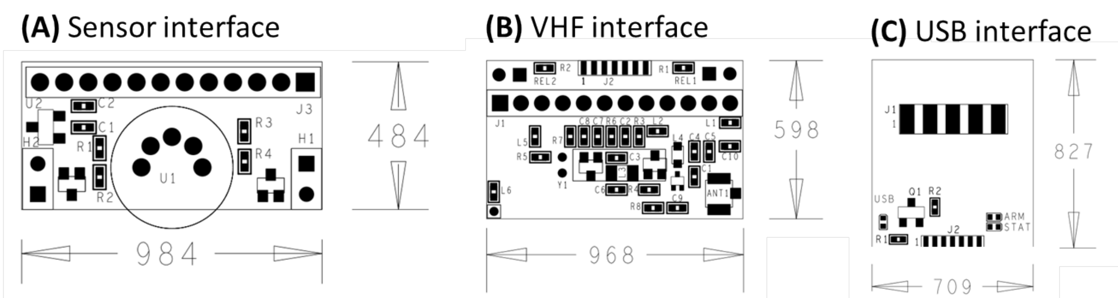

Figure 6 Three interconnect boards used to interface between the tag sub-assemblies.

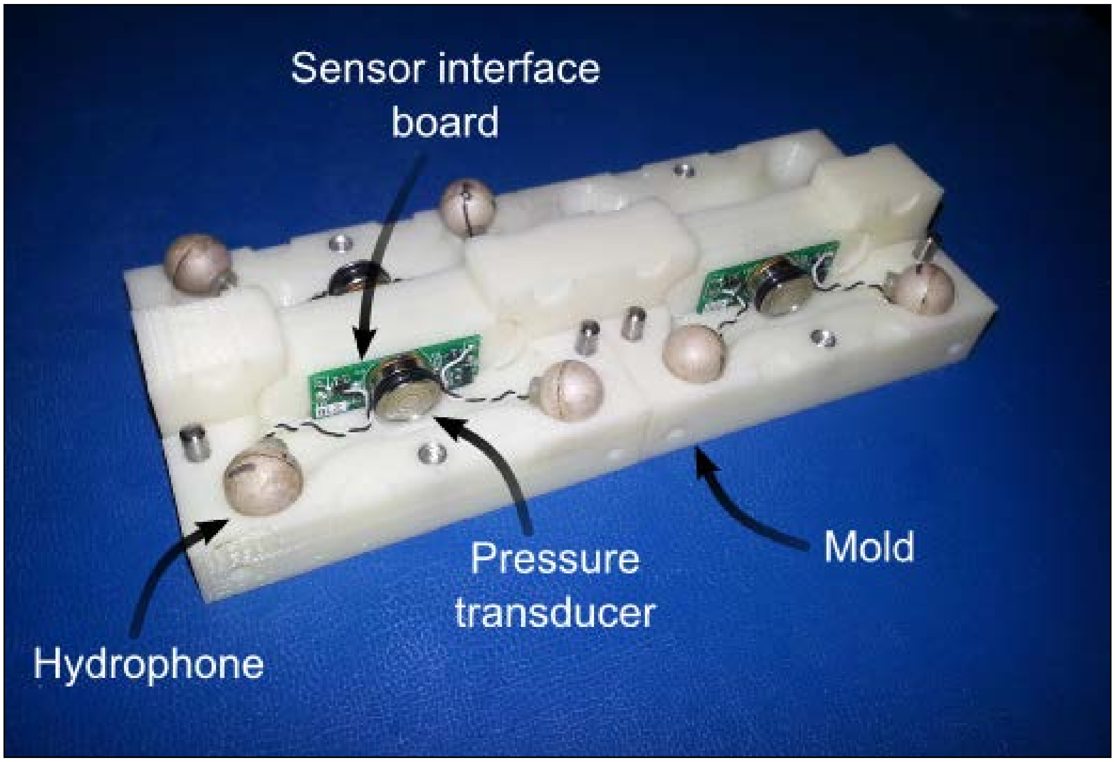

Figure 7 A picture of the mold used to encapsulate multiple sensor assemblies simultaneously. The hydrophones, pressure transducer, and interconnect board are shown positioned in the mold.

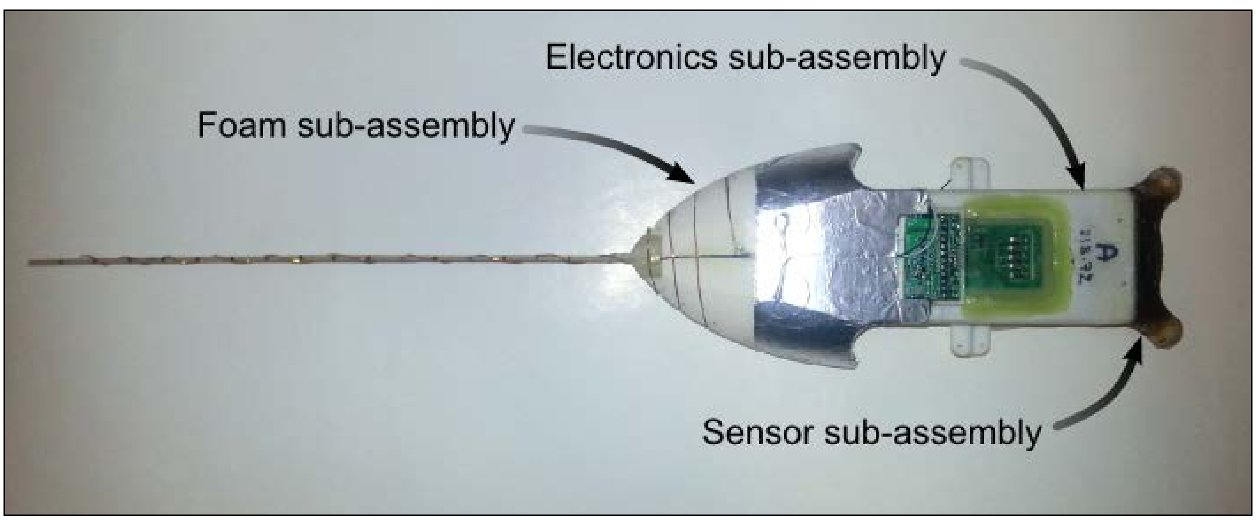

Figure 8 A picture of the sub-assemblies combined into a single unit before encapsulation.

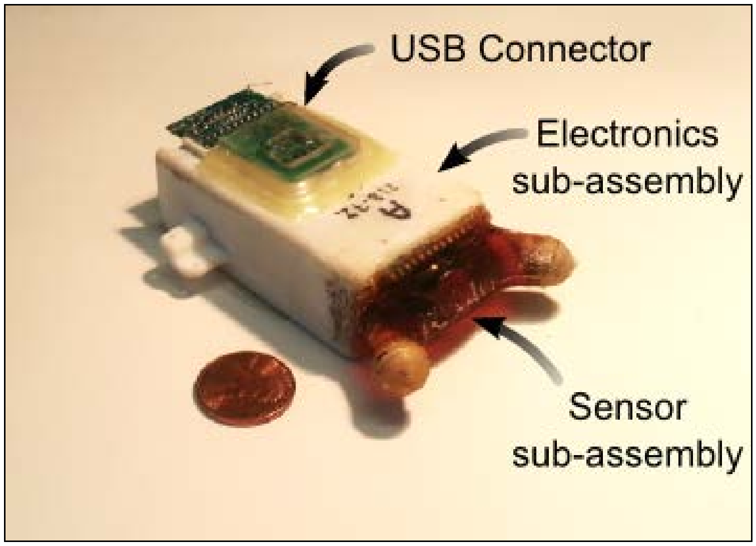

Figure 9 A picture of the combined electronics and sensor sub-assemblies used in the lab based pressure testing. Vacuum investment was used to encapsulate the electronics in epoxy.

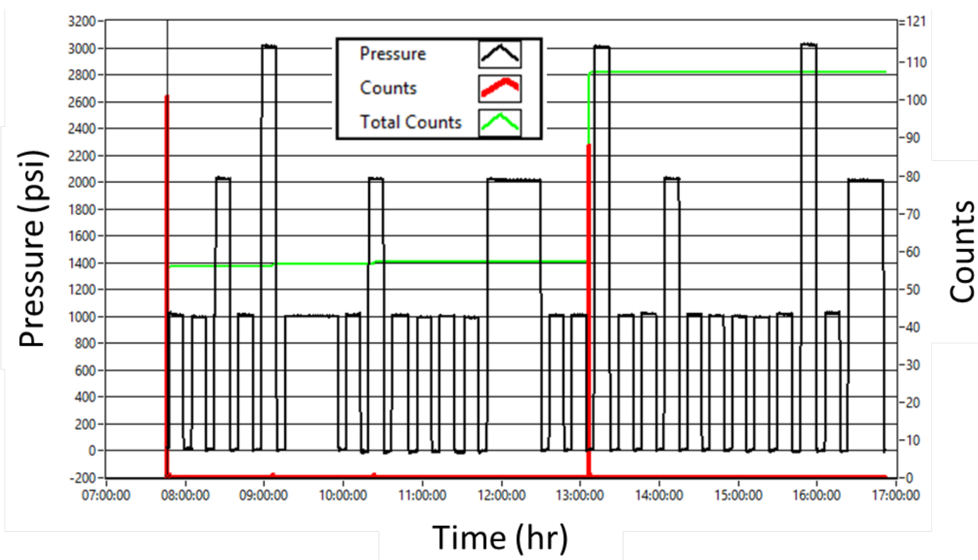

Figure 10 Pressure testing results that followed the Test 2 protocol collected at the Blake facility. During the course of the testing the tags were cycled to 1000 psi nineteen times, 2000 psi five times, and 3000 psi three times.

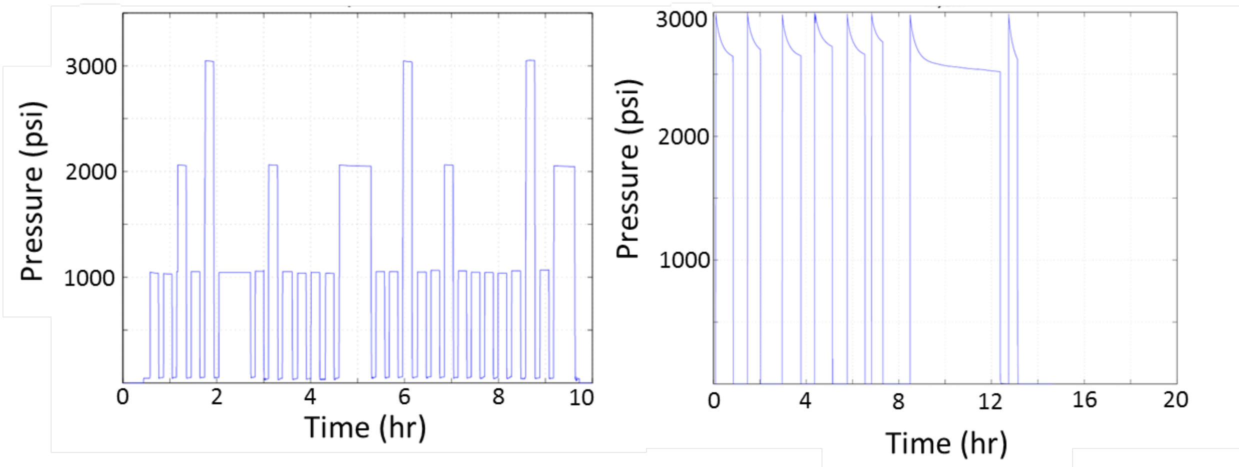

Figure 11 Representative pressure testing results from the Blake facility (left) and the Smith facility (right) that followed the Test 2 and 3 protocols respectively.

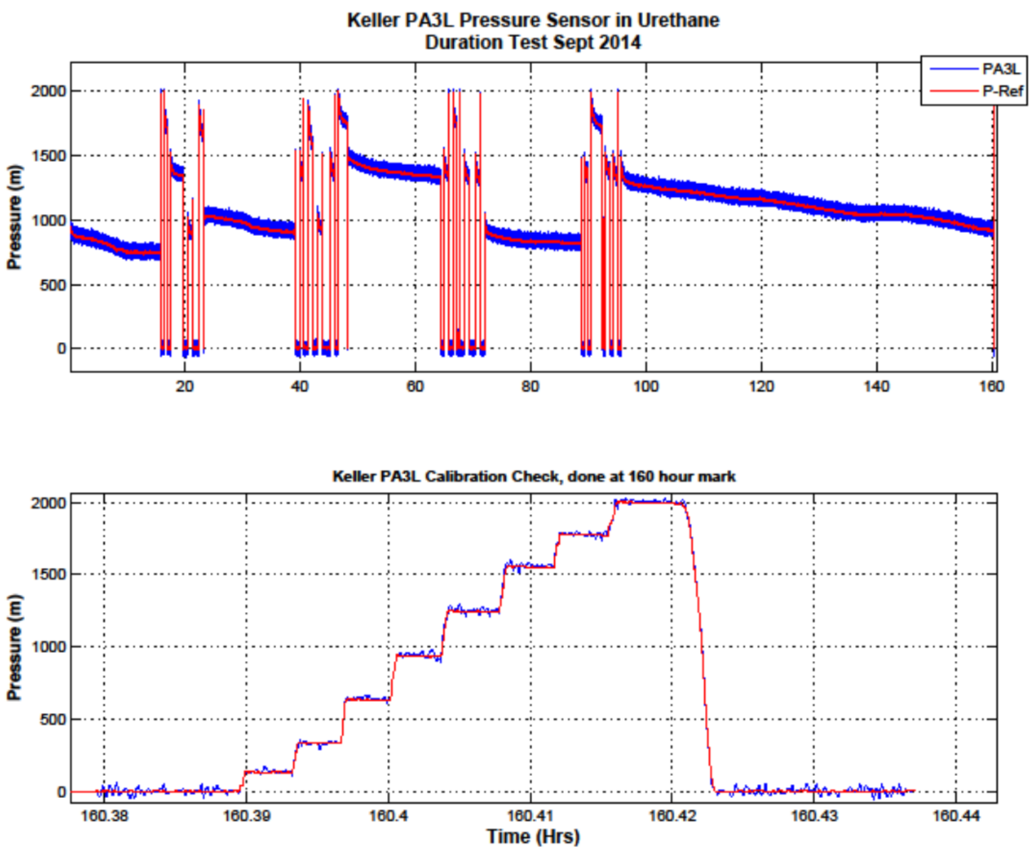

Figure 12 PA3L pressure and reference sensor data collected over the course of 160 hours in the Smith pressure testing chamber.